NATIONAL BUREAU OF STANDARDS REPORT

7358

AN INVESTIGATION OF THE FIRE-INDUCED FLOW REGIME AT THE SINGLE VENTILATION OPENING IN A MODEL ROOM ENCLOSURE

by

George D. Van Arsdale

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U. S. DEPARTMENT OF COMMERCE
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ABSTRACT

Three methods for determining the boundary between entering air and exiting smoke at the single ventilation opening in a model room enclosure are presented: temperature profile, optical distortion due to thermal gradients, and differential CO_2 concentration. Preliminary tests with the first two methods gave reasonable and consistent results.

A technique for measuring smoke and flame velocities near ventilation openings has been explored. By means of interrupted streak photographs of small, inert particles, velocities up to about 10 fps in one plane may be measured.

BACKGROUND

As part of a project exploring the use of models for investigating fire behavior in buildings, it was desirable to study the flow of air and smoke at the opening in a model room enclosure. It had been found that the weight rate of combustion of the fiberboard fuel cribs within the enclosure was related to the "ventilation parameter," $A\ H^{\frac{1}{2}}$, where A is the area and H is the height of the opening. This parameter is of the same form as the expression for non-compressible gas flow through an orifice $Q = k\ A(2gH)^{\frac{1}{2}}$, where Q is volume rate of flow, k is a constant, A is the cross sectional area, g is the gravitational constant and H is the static head change.

It had been observed in these burning experiments that in the case of a single opening in an enclosure, air would enter the enclosure through the lower portion of the opening, and smoke would leave through the upper portion. At any given time, a fairly well defined boundary existed between the two, but the boundary was observed to vary with the particular burning stage i.e., ignition, steady-state burning, and decay. It would be expected that the boundary would be elevated as the oxygen in the enclosure was consumed and steady-state was approached.

The velocity distribution, when integrated to obtain total air and gas flow, should give an indication of the combustion processes involved. Some of the data might indicate a change in mechanism, depending upon the degree of ventilation. In addition, knowledge of smoke (and flame) velocities at the opening in the model room enclosure should be useful in estimating the effects at windows and doors during fires in full-size rooms.

This report summarizes preliminary studies dealing with: I. Boundary Location, and II. Velocity Distribution.

PART I. DETERMINATION OF THE BOUNDARY BETWEEN ENTERING AIR AND EXITING SMOKE.

1. Introduction

The boundary between the air and the smoke may be defined by either the point of zero velocity or the point of maximum temperature gradient. While it is not known whether or not these points (or actually lines) are coincident, they are in close proximity. The boundary could be defined as the point where clear air stops and smoke begins. However, this would be extremely difficult to detect, even photographically, because of the "neutral" color and lack of contrast of the smoke. With all of these definitions, the random fluctuations of the turbulent flames must be considered.

a. Temperature Profile

Since the smoke and gases leaving the enclosure will be at a higher temperature than the ambient air which is entering the enclosure, it is relatively simple to measure the temperature of the gas at the opening, and determine at what height the first (and only) sudden change occurs. A convenient way for measuring this temperature profile is by means of a series of stationary thermocouples. However, since the temperature measuring devices should not interfere unduly with the gas flow, a better arrangement seemed to be a single thermocouple mounted on a traverse mechanism. This would not be limited in precision by thermocouple junction spacing, and the recording of data would be simpler.

The apparatus used in this experiment consisted of a No. 24 gage (0.020 in.) chromel-alumel thermocouple probe mounted on a traversing mechanism. The probe was made of 1/4" o.d. porcelain two-hole-tubing and presented a very small obstruction to the gas flow. The traversing mechanism was built around a hand-operated hydraulic jack, the piston movement of which was read on an attached scale. The thermocouple leads were connected directly to the input of a millivolt-range, dual channel recording potentiometer without cold junction compensation.

The thermocouple was made to traverse the opening in about four minutes. A second thermocouple probe with a 4.5 cm separation was installed and its output recorded simultaneously. A typical temperature profile during the initial stages of burning is shown in Figure 1, no attempt having been made to measure absolute temperature. The height of the boundary, h, is clearly defined.

b. Optical Distortion

It is well known that thermal gradients produce a bending of light rays which results in distortion in the image of objects. This is due to the changes of refractive index of the air and the resulting prism effect. This principle is employed in Schlieren photography, and explains the "dancing" of hot pavement. A very simple way of determining the location of the boundary is to observe the distortion of a grid, by the smoke and flames. Through the use of photography, fairly accurate measurements may be made conveniently. However, since the grid and the hot gases are not in the same plane, parallax errors must be considered. By placing the camera at the same level as the boundary, the error will be small and the use of a telephoto lens (half of a pair of 7 x 50 binoculars for example), should reduce the error to negligible proportions.

Several preliminary photographs were made with an Exakta 35 mm single-lens-reflex camera, coupled with a pair of 7 x 50 binoculars. With several different combinations of grid and illumination, good results were obtained. The camera-binocular combination had an effective opening of f 7.0. Using the setup shown in Figure 2, the result of a typical optical distortion test is shown in Figure 3.

c. Differential CO_2 Concentration

The products of combustion which leave the opening of the enclosure contain, say 10% CO_2, whereas the ambient air contains less than 1%. CO_2 is an excellent absorber of infrared radiation, especially that with a wavelength of 4.2 microns. By placing an infrared source on one side of the box, and a detector (i.e., a thermocouple) on the other side, the height of the boundary could be measured. A series of fixed detectors or a single movable one could be used. The same sort of scheme could be worked out for visible radiation, but there is insufficient natural contrast to be detected photoelectrically. Any material which was introduced into the enclosure for the purpose of producing dense smoke would seriously affect the combustion processes.

While this method would probably give good results, other methods appear more expedient for this particular series of experiments.

2. Discussion

Reasonable and consistent results have been obtained by both temperature profile and optical distortion methods. A summary of the results from a limited number of boundary determination tests is shown in Figure 4. The optical method has the advantages of measuring the boundary over the whole front of the enclosure, and of not disturbing the gas flow at all. It gives a nearly instantaneous value of the boundary location, but the time period can be varied by changing camera exposure time. Some distortion of the grid may be traced to the lens system, but this may be accounted for by comparing the photograph with one taken without any fire. Distortion may be reduced by using a smaller lens opening on the camera and adjusting the exposure time accordingly.

While the optical method is definitely superior for instantaneous measurements, a variation of the thermocouple method offers possibilities for continuous measurements. Two thermocouples, displaced vertically from each other about 5 mm, could be differentially connected so as to respond to temperature difference. The height of the probes could be regulated by a servo system to maintain a maximum temperature difference and thus measure boundary height as a continuous function of time.

Either Schlieren photography or interferommetry could also be employed to measure this boundary, but the expense involved does not appear justified.

PART II. TECHNIQUE FOR MEASURING SMOKE AND FLAME VELOCITIES NEAR VENTILATION OPENINGS.

1. Introduction

Gas velocity measurements often present many problems. The most common method is to measure the pressure drop across an orifice through which the fluid is flowing and compute the velocity from Bernoulli's equation. Another method involves measurement of dynamic pressure with a Pitot-static tube [1]. While the first method is suitable for a closed duct, with gas of uniform temperature and composition, it would be difficult to apply at the entrance to a model room enclosure. The second method, while possible, was not considered practical due to the slow response time of available manometers sufficiently sensitive to measure the small pressure changes involved. A method which is often used when low velocities are to be measured is the hot-wire anemometer. This device, however, is temperature-dependent and compensating arrangements appear to be inadequate. A cup-type anemometer or a calibrated "fan blade" offer too much resistance to be practical.

Faced with this array of unsuitable methods, it was decided to turn to a flow visualization technique. If small particles are released in a flowing stream, they will tend to follow the streamlines. The more closely the densities of the particles and the gas match, the more the particles will follow the gas flow. Ideally, "marked" (i.e., ionized or radioactive) molecules of gas could be used as they would follow the streamlines exactly, and cause a minimum of flow interference. In practice, however, these would be difficult to work with. It then becomes necessary to accept some loss in accuracy and use solid particles.

2. Test Method

In this test method, the distance which small particles travel in a given time was measured, and their velocity computed. The particles were introduced into the gas flow by a dispenser of the type shown in Figure 5. All of their initial velocity was in a direction in which the flowing gases have no velocity component. The distance which the particles travelled was measured from a photograph, taken at a distance of about 2 feet. Light was provided by a source located beneath the enclosure opening, which projected a narrow (i.e., 1-inch) band of light upward. A mirror (or second source) located above and in front of the enclosure served to provide more even illumination.[2].

The timing was provided by a mechanical auxilliary shutter which was placed in front of the camera. This device is essentially a pitchless "fan," driven by a constant speed motor, and was provided with a protective guard housing.

The whole apparatus was set up as in Figure 6, and provided with thermal radiation shields to protect the camera, dispenser, etc. It was necessary that the shield opposite the camera be a dull black, in order to provide a contrasting background for the particles. A scale for distance measurements and a card bearing the test number was inserted into the camera's field when each photograph was taken.

3. Materials and Procedures

The powder which was used in most of the preliminary tests was commercial perlite although magnesium oxide powder or commercial talcum powder may also be used [3]. The perlite was passed through sieves in order to obtain a fairly uniform size sample. It was found that the best sizes were between #200 sieve(74 microns) and #70 sieve (210 microns). While finer particles follow the streamlines better, they tend to cake in the dispenser. In a humid climate such as is common in Washington, D. C., in the summer, it is helpful to store the powder in a desiccator prior to use. It would be possible to use a less inert particle, such as sodium bicarbonate, but this decomposes very rapidly at the high temperatures ($\sim 725°$) encountered. For some measurements, the luminescence of such particles would help, and thereby justify their use.

The powder dispenser essentially shakes powder into a stream of air which carries the powder out of the delivery tube. There are several adjustments which may be used to vary the powder flow. The particle velocity is controlled by the air supply pressure, while the amount is controlled by the screen size, the vibrator impulse, and the differential pressure between the magazine and the delivery tube (fixed in this series). The delivery tube should be aimed more or less toward the camera, and can be adjusted in height as needed.

The chopper which was used in the preliminary tests consisted of two 30-degree blades driven by an 1800 rpm synchronous motor. A "light" period of 1/72 sec is followed by a 1/360 sec "dark" period; thus a particle which moved 5/6 in. in each dash, was traveling at 5 fps. The camera shutter was left open for 1/5 sec., in order that each particle leave "dashes" on the photograph. The camera was placed so that the chopper blade traveled at right angles to the camera's focal plane shutter, reducing the foreshortening effect.

Any good camera capable of focusing at the required distance is satisfactory. In the preliminary tests, an Exakta single-lens reflex, 35 mm camera was used. A good black and while film such as Plus-X or Tri-X should be used, with exposure depending upon film and illumination. It was found that f.22 at 1/5 sec gave good results with Tri-X and two photoflood lamps. A telephoto lens is helpful, as larger particle images are easier to measure. The measurements may be made directly from a projected negative, or from the negative itself with a microscope.

The illumination should be concentrated in a narrow band, so as to keep all illuminated particles within the camera's depth of field. A slit opening, fitted with a cylindrical condensing lens would ensure such a band. However, heat produced by incandescent lamps must be considered in the design of their housing.

Under some conditions, it is desirable to provide the camera with a filter, e.g., light blue, to reduce the image of orange flames. This also protects the camera lens from heat, flying ash particles, etc.

4. Discussion

The method of velocity measurement described herein offers a potentially flexible and accurate means for studying the flow in the vicinity of flames. It has been used for this purpose by several workers in the field, c.f. Lewis and von Elbe[3]. The principal merits for this method lie in its simplicity (apparatus which can be operated by one man), and its minimal disturbance of the flow patterns. A sample record of fire-induced particle tracks at the opening of an enclosure is shown in Figure 7.

The powder dispenser gradually evolved from a gravity feed type. In this case, it was noted that many particles failed to make the nearly 180° direction change necessary to follow the rising gas flow. In spite of the seemingly overwhelming effect of the "drag" or aerodynamic lifting force (see appendix), the mass and initial velocity of the particles seems to have some effect. This may be aggravated by the tendency for flames to travel up into the vertical delivery tube and to fuse particles together within the tube.

One difficulty inherent in the forced-feed dispenser is the effect of its air stream on the flow patterns which are being studied. As the air is directed into the upper part of the opening, in the horizontal direction, the particles are carried away from the enclosure without becoming part of the hot gas flow. The stream of supply air, however, helps keep the delivery tube (1/4-in. copper) cool. The tube itself causes some interference with the gas flow, but this is small, and not in the region being studied. The important feature of the dispenser is the restriction of initial particle velocity to a direction in which the velocity of the hot gases has no significant component.

The chopper is quite straightforward, the blade geometry having been selected to give a reasonable interval. A speed check with a stroboscopic tachometer indicated that the chopper was running exactly at synchronous speed for constant line frequency.

There is some question as to the best film to use. At the short distances suggested, a medium speed film such as Plus-X is probably best, although at a greater distance the more sensitive Tri-X is better. The film should be processed according to the manufacturer's directions, and kept free of dust particles.

The band lighting was used to obscure particles which are out of the camera's depth of field. It also served to keep the background darker, thus providing maximum contrast between the particles and the background. The heat produced by photoflood lamps was a major problem in their use. Although flash lighting eliminated this problem, it was bothersome. A stroboscope could be used, but its flash duration is far too short for the chopper. The stroboscope itself could be used to provide the timing interval, but this would produce a series of dots, rather than dashes on the photograph. In some cases, dots could be used satisfactorily, but it is extremely difficult to distinguish individual particles among an array of dots.

The question of filter use was not completely resolved. In some cases a blue filter seemed to help. In other tests, the photographs taken without a filter were far superior. Apparently, the effect of a filter depends upon the emission of the particle (if any) and the emission of the flames. These would vary with temperature.

5. Conclusions

The method of velocity measurement described is ready to be tried in full-scale tests. Some refinements will be necessary before good reliability can be maintained, but this should not require a great deal of effort.

The velocities of air, smoke, and flame in the same region may be measured with a fair degree of accuracy. Before many tests are made, a calibration of the system in a duct would be in order. A certain amount of inaccuracy is inherent in the system because of the difference in densities of the gases and the particles. However, this is not considered of great magnitude in the application for which the method was developed.

6. References

[1]. R. T. Gautreau, NBS Technical Report No. 7008, 3 Nov. 1960.

[2]. M. Allen and A. J. Yerman, "Neutral Density Beads for Flow Visualization" ASME Symposium on Flow Visualization, New York, 30 Nov. 1960.

[3]. B. Lewis and G. von Elbe, Journal of Chemical Physics, Vol 11, (1943) 75-84.

[4]. V. Streeter, Fluid Mechanics, McGraw-Hill, New York, (1958).

7. Appendix

Fluid Force on Particles

Assumptions: (only approximate)

$U = 5$ fps, $T = 1500°F$ $\quad \rho$ and μ of smoke

$\approx \rho$ and μ of dry air, d = wetted perimeter/4

$$= \frac{125}{4} \text{ cm}$$

$$R_e = \frac{\rho U d}{\mu} = \frac{5}{1.47 \times 10^{-3}} \quad \frac{125}{4 \times 2.54} = 4180$$

this is in the so-called transition range

$$F_{drag} = C_d \; A \; \frac{\rho \; U^2}{2g}$$

with a particle having $\rho \approx 7.85$ lb/ft^3, D = .0058"
(will just pass through #100 sieve)

$C_d = 0.4$ from Tables - Streeter [4]. p. 170

$$F_d = \frac{(0.4)\;(1.83 \times 10^{-7})\;(7.85)\;(25)}{2\;(32.2)}$$

$$= 2.23 \times 10^{-7} \text{lbs}$$

Using the same assumptions, the gravitational force is

$$F_g = \rho V = \frac{4\pi}{3} r^3 \rho = \frac{4\pi}{3\;(1728)} \left(\frac{.0058}{2}\right)^3 (7.85)$$

$$= 4.63 \times 10^{-12} \text{lb}$$

Since $2.23 \times 10^{-7} >> 4.63 \times 10^{-12}$, gravity effects are small compared with the force of the fluid.

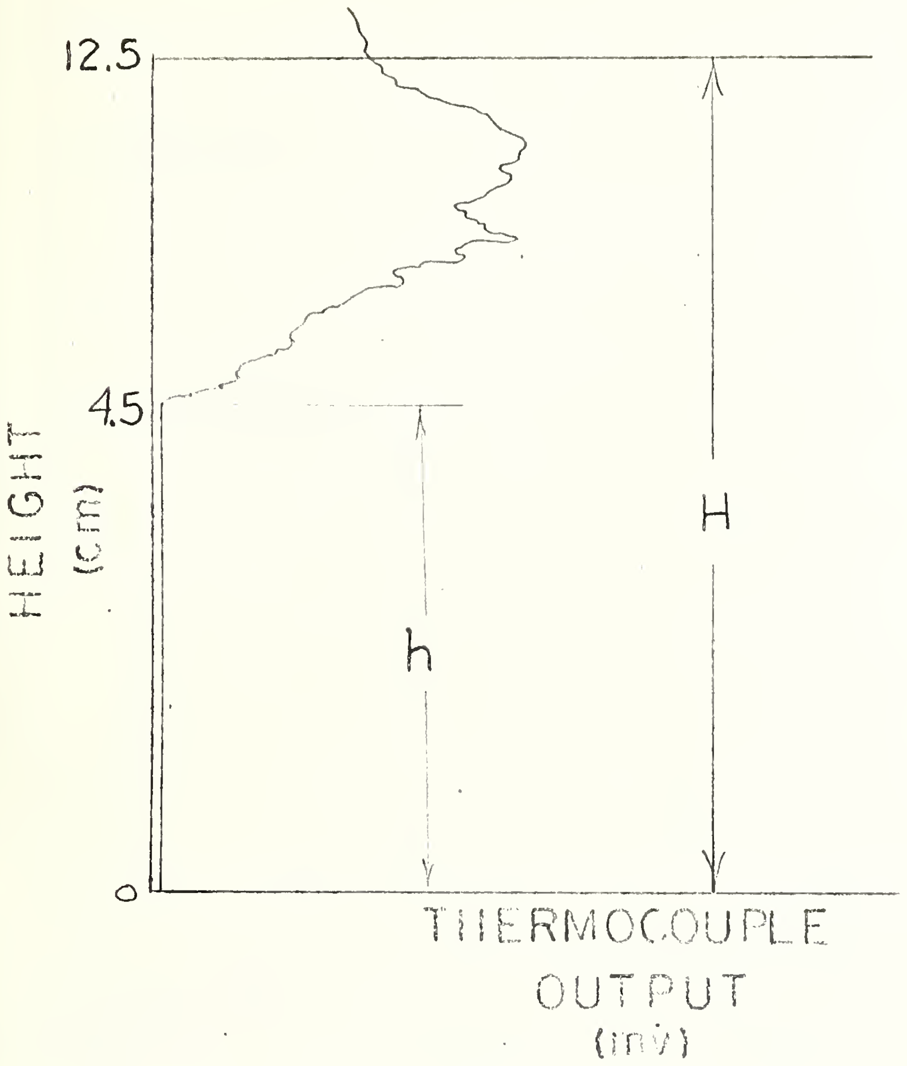
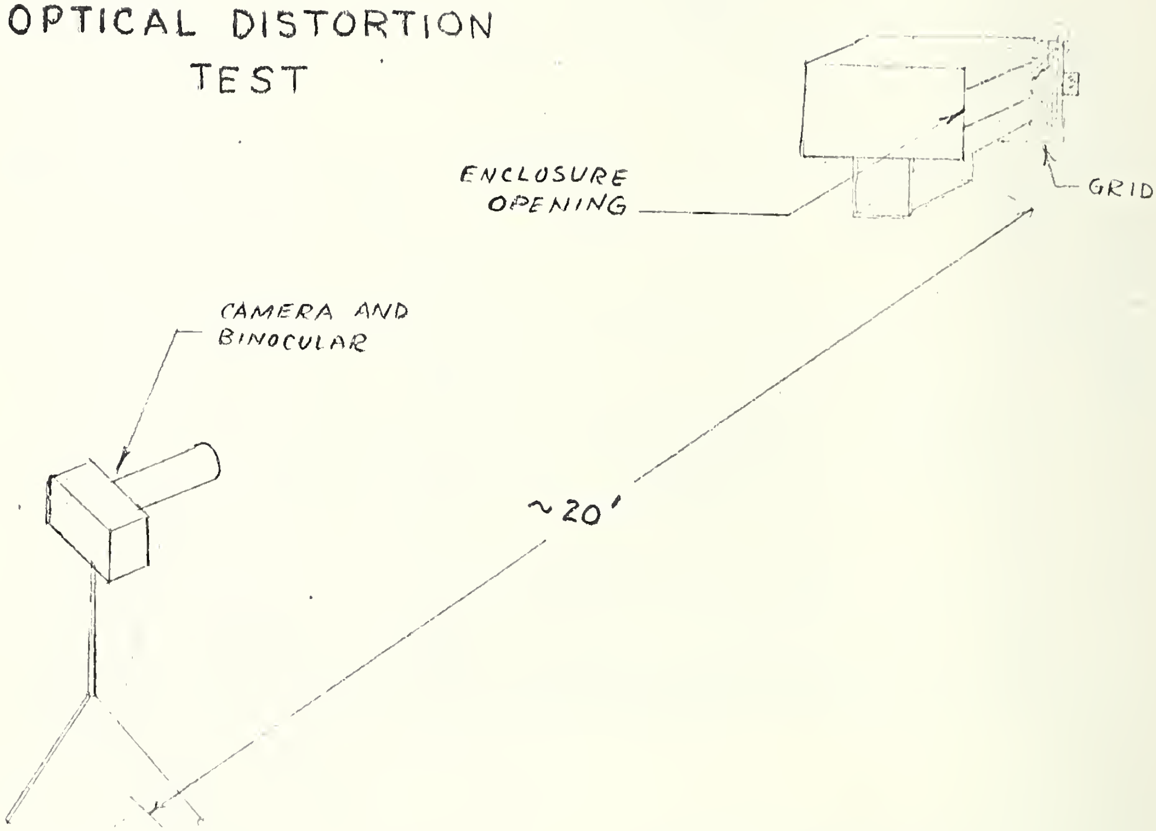


FIG. 1. "TYPICAL" TEMPERATURE PROFILE

h = indicated height of boundary, H = height of opening
(Heights not to scale)

FIG. 2. OPTICAL DISTORTION TEST



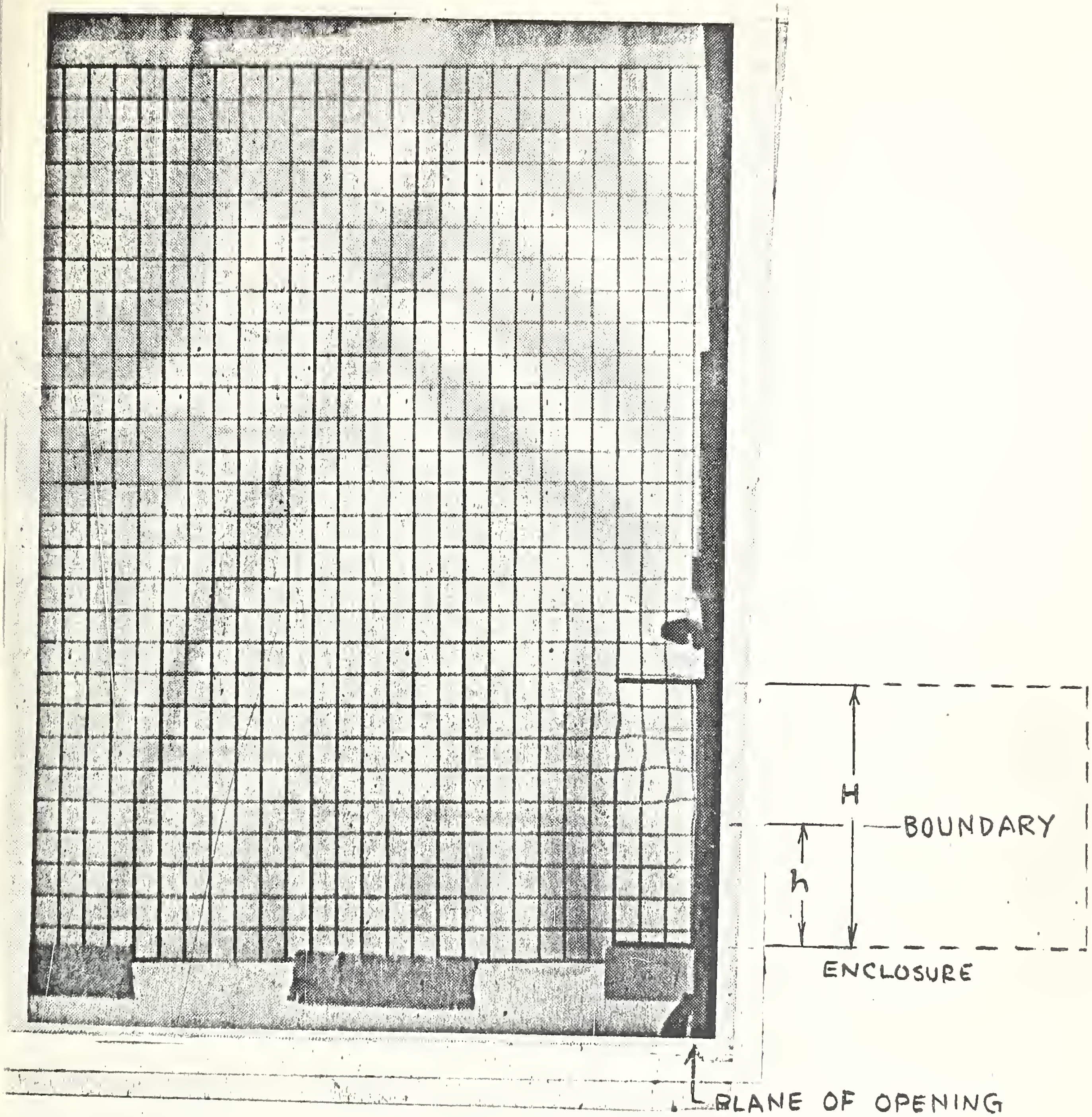


FIG. 3. OPTICAL DISTORTION OF GRID BY HOT GASES EXITING AT OPENING IN MODEL ROOM ENCLOSURE

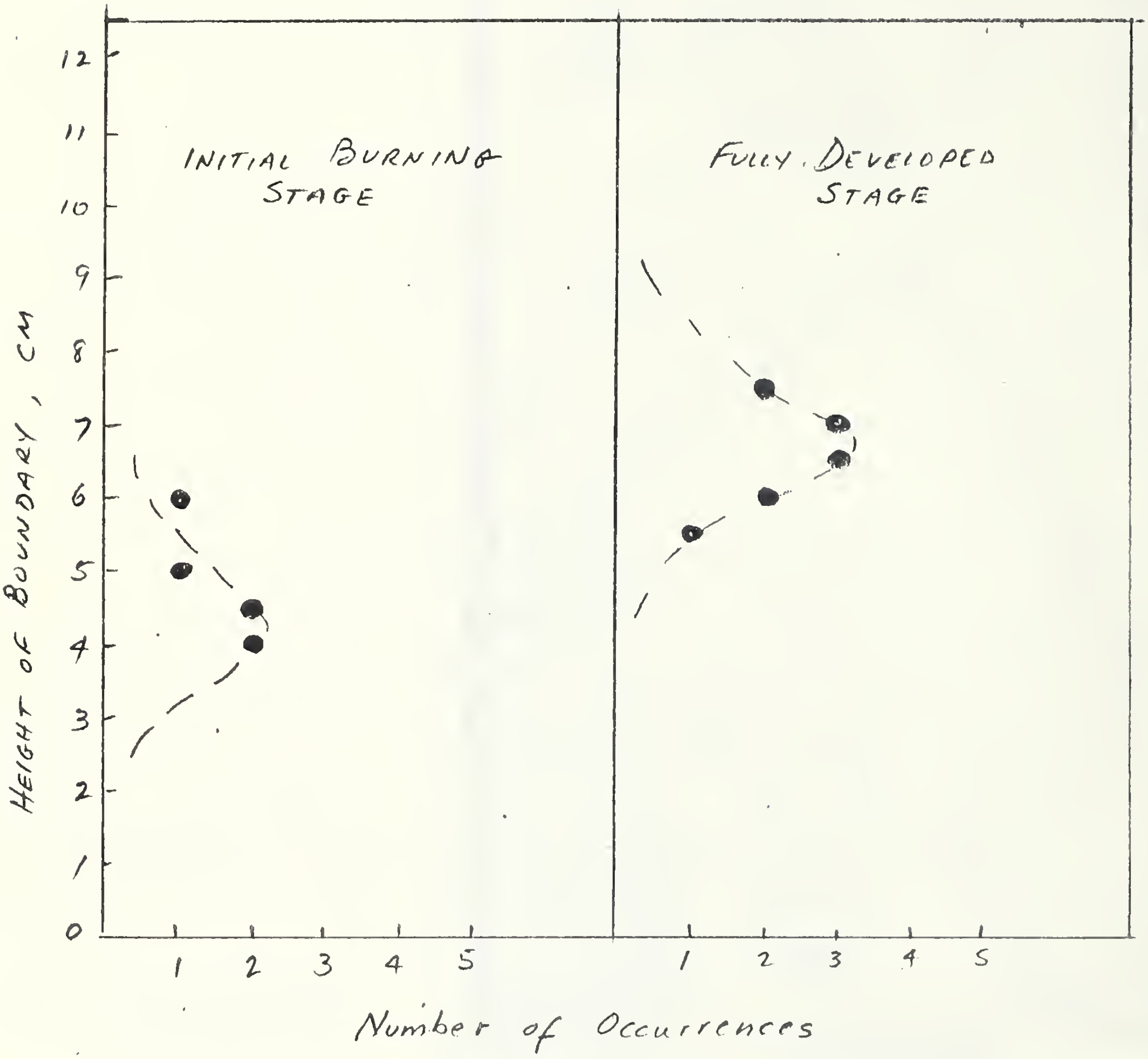


Fig. 4. Distribution of Boundary Height from Temperature Profile and Optical Distortion Tests

Total Number of Measurements : 17

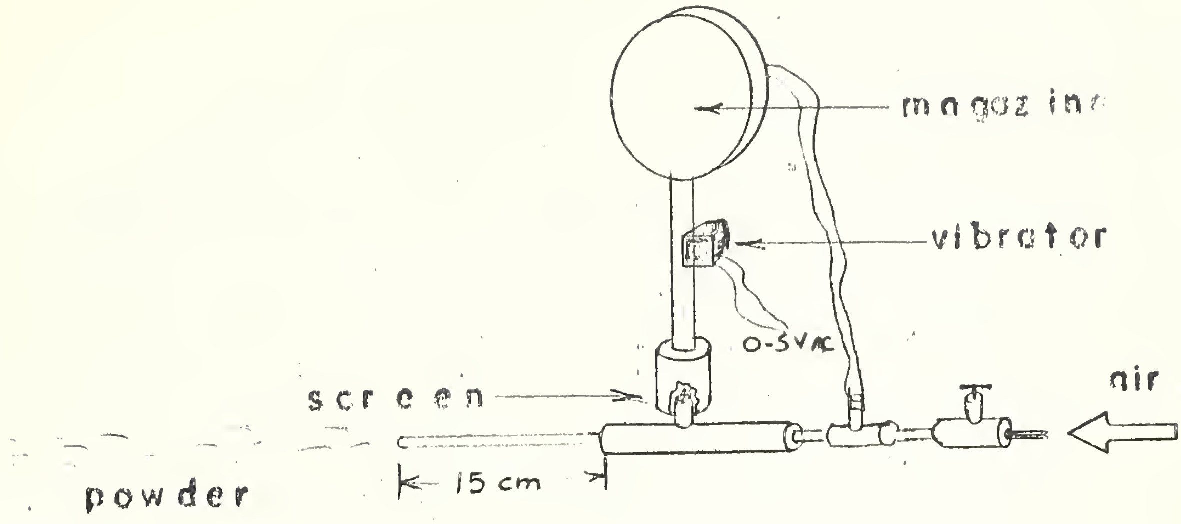
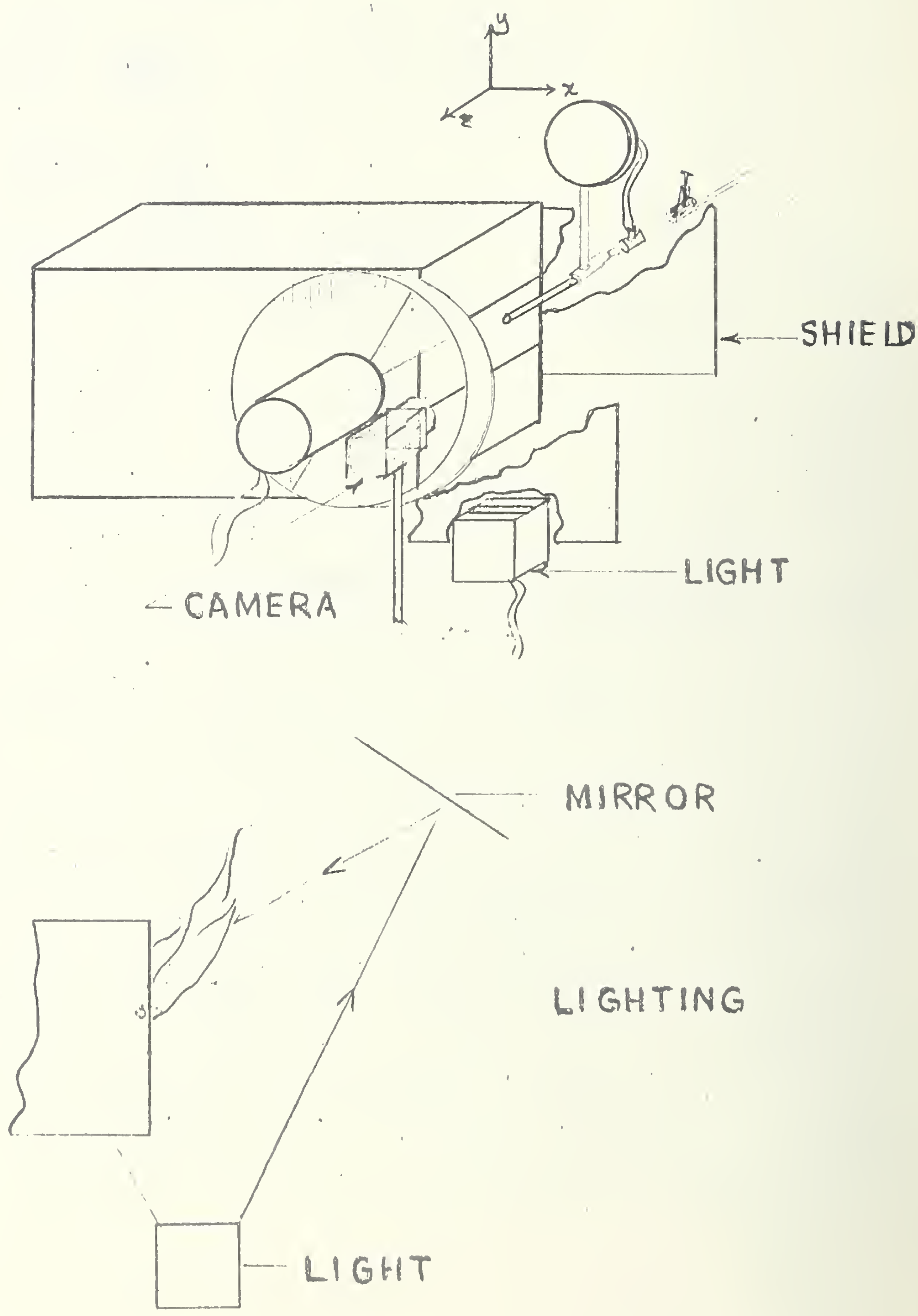


FIG. 5 POWDER DISPENSER

FIG. 6. VELOCITY MEASUREMENT SET-UP



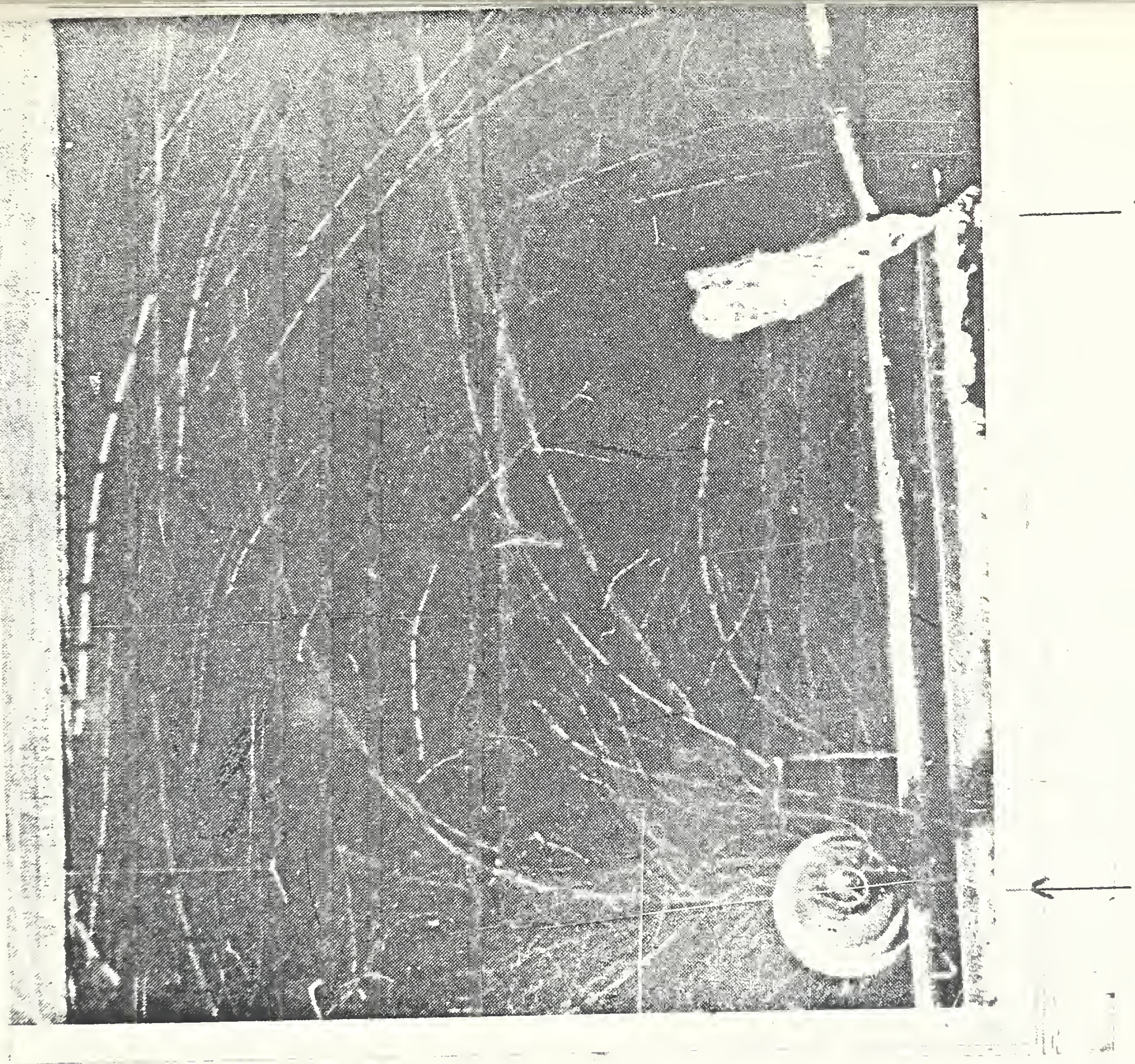


FIG. 7. PHOTOGRAPH OF FIRE-INDUCED PARTICLE TRACKS AT OPENING OF MODEL ROOM ENCLOSURE - CAMERA DISTANCE 2 FEET

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